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on Recovery of Space Vehicles
on August 31 - September 1, 1960

AERODYNAMIC REQUIREMENTS FOR LONGITUDINAL STABILITY OF WINGED SPACE VEHICLES DESCENDING INTO THE EARTH'S ATMOSPHERE AT VERY HIGH ANGLES OF ATTACK

By Ernie L. Anglin and Stanley H. Scher*

Among the many categories of vehicles which have been proposed for use as atmospheric reentry vehicles are winged craft which enter the earth's atmosphere at very high angles of attack. Some vehicles have been proposed for reentry at 90° angle of attack, while others are to come in at 50° to 60° angle of attack. In either case, the craft is to decelerate from orbital velocity and altitude to some velocity and altitude at which a transition maneuver to low angle-of-attack flight would be made prior to a normal landing.

A study has been made to determine combinations of aerodynamic design factors which would enable such a craft to descend toward the earth without tumbling end over end and without oscillating at magnitudes and/or frequencies beyond those which may be considered as reasonable for a manned vehicle.

The conditions tested are for terminal velocity at sea level, 50,000 feet, 100,000 feet, and 200,000 feet. The longitudinal aerodynamic requirements are presented in terms of the usually seen longitudinal stability derivatives C_{m_α}, C_{L_α}, and C_{m_q}, which are respectively the static pitching moment coefficient due to angle of attack, the lift coefficient due to angle of attack, and the damping in pitch coefficient. The requirements were determined from the results of motion calculations of a descending vehicle for various combinations of the aerodynamic factors. A digital

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computer was used for the motion calculations. The computer solved the three-degree-of-freedom equations of motion and the auxiliary equations shown in figure 1. As may be noted in the equations of motion, the C_L versus α aerodynamic data, which will be presented later, was broken down into its two components along the X and Z body axes as a computer convenience.

Although problems of lateral stability will also have to be considered for winged reentry vehicles, this investigation was confined to longitudinal motions. Some available free-body tests with dynamic models indicated the feasibility of making separate studies of the longitudinal and lateral motions. In the present investigation, the approximate angle of attack for reentry was 90°. However, the approach and methods used are applicable for any desired reentry and trim angle of attack.

This study may be considered as an extrapolation from one of the free-body tests. The model used was a flat-plate delta-shape with an apex angle of 76°. The behavior of the free model in descent is shown in the accompanying motion pictures which were made in the Langley 20-foot vertical wind tunnel.

The technique used in the motion calculations involved inserting initial values for angle of attack and descent velocity into the computer for a given combination of aerodynamic, mass, inertia, and dimensional inputs. The motion was then calculated by the computer. Input combinations which indicated decreasing oscillations toward the trim angle of attack were said to be stable conditions, whereas combinations indicating steadily increasing oscillations were said to be unstable conditions.

No control deflections were used in either the experimental or analytical studies. The objective was to determine the degree of inherent dynamic stability by the ability to damp oscillations and seek a trim attitude for the various combinations of inputs used, and to determine the relative importance of these inputs.

The static and oscillation aerodynamic characteristics for the free-body model, as measured in the Langley free-flight tunnel, are shown in figure 2. This data was measured at a Reynolds number of approximately 160,000, based on mean aerodynamic chord.

A time history of the angles of attack obtained from the basic calculated result are compared in figure 3 with the time history from the motion pictures shown previously. The calculated result used the aerodynamic data of figure 2 as a computer input. As may be noted, the calculated results agree very closely with the experimental results.

The range of lift coefficient versus angle of attack used in this study is shown in figure 4, with that for the basic delta wing indicated. The range of static pitching moment versus angle of attack used is shown in figure 5, with that for the basic delta wing again indicated. For calculations resulting in decreasing oscillations, the aerodynamic data used was only that along the linearized constant-slope portions of the C_m and C_L versus α curves. Therefore, it appeared justifiable to use C_{m_α} and C_{L_α} in defining magnitudes of static aerodynamic pitching moment and lift required for longitudinal stability. For calculations in which diverging oscillations or tumbling was indicated, the computer had to use the complete non-linear C_L versus α and C_m versus α curves.

All the results obtained directly from the computer consisted of time histories of a number of variables showing attitude and linear and angular velocities. Among these variables are angle of attack, pitching velocity, rate of descent, resultant linear velocity, altitude, and the horizontal displacement of the center of gravity. A typical plot of a time history is shown in figure 6. This plot is for the basic model shown in the motion picture earlier.

The results of the investigation indicating aerodynamic requirements for longitudinal stability are shown in figure 7 as functions of C_{L_α} and C_{m_q}. This figure is for a given value of C_{m_α} and altitude. Variations in C_{L_α} appeared to have a major effect on the inherent stability of the subject configurations. Large negative values in general led to larger oscillations with greater damping moment, C_{m_q}, shown to be necessary for stability. Combinations falling above and to the left of the line indicate stable combinations while points to the right and below the line indicate unstable combinations. It may be noted that for certain values of C_{L_α}, even a positive value of C_{m_q} does not cause an unstable motion.

Changing values of C_{m_α} did not affect the location of the stability division line. For any value of C_{m_α} used, the stability requirements in terms of C_{L_α} and C_{m_q} appear to be the same.

Increasing altitude should cause an increased damping to be necessary for stability due to the fact that the static aerodynamic coefficients are non-dimensionalized by a velocity-squared term while the damping coefficients are non-dimensionalized by velocity raised only in the first power. However, if an increased damping due to altitude increase was necessary here, it was too small to be noticeable.

Variations in C_{m_α} had a major effect on the period of the oscillations, as shown in figure 8. The lower values of C_{m_α} gave the longer periods. Increasing altitude gave slightly longer periods, although the effect was not very great. C_{L_α} and C_{m_q} variations apparently had no effect on the period.

The stability requirements in terms of C_{L_α} and C_{m_q} may be a function of Mach number or velocity due to the methods of non-dimensionalizing static and damping coefficients discussed previously.

The lateral stability requirements should also be investigated for reentry vehicles. In addition, during phases of the flight at which transition is made to more normal low-angle-of-attack flight, the problem of stability and control may become more complex. Analytical studies of such motions may be necessary using non-linear aerodynamic data and six-degree-of-freedom equations of motion.

EQUATIONS OF MOTION

$$\dot{q} = \frac{\rho V_R^2 S d}{2 I_y} C_m + \frac{\rho V_R S d^2}{4 I_y} C_{m_q} q$$

$$\dot{u} = g \cos\alpha - wq + \frac{\rho V_R^2 S}{2m} C_x$$

$$\dot{w} = g \sin\alpha + uq + \frac{\rho V_R^2 S}{2m} C_z$$

Auxiliary Equations

$$\alpha = \cos^{-1} \frac{u}{V_R}$$

$$V_V = -u \sin\theta_e + w \cos\theta_e$$

$$\dot{\theta}_e = q$$

$$h_2 = h_1 - V_V(\Delta T)$$

$$C_x = C_L \sin\alpha - C_D \cos\alpha$$

$$V_L = \sqrt{V_R^2 - V_V^2}$$

$$C_z = -C_L \cos\alpha - C_D \sin\alpha$$

$$HT_2 = HT + V_L(\Delta T)$$

Figure 1 — Equations of motion and auxiliary equations

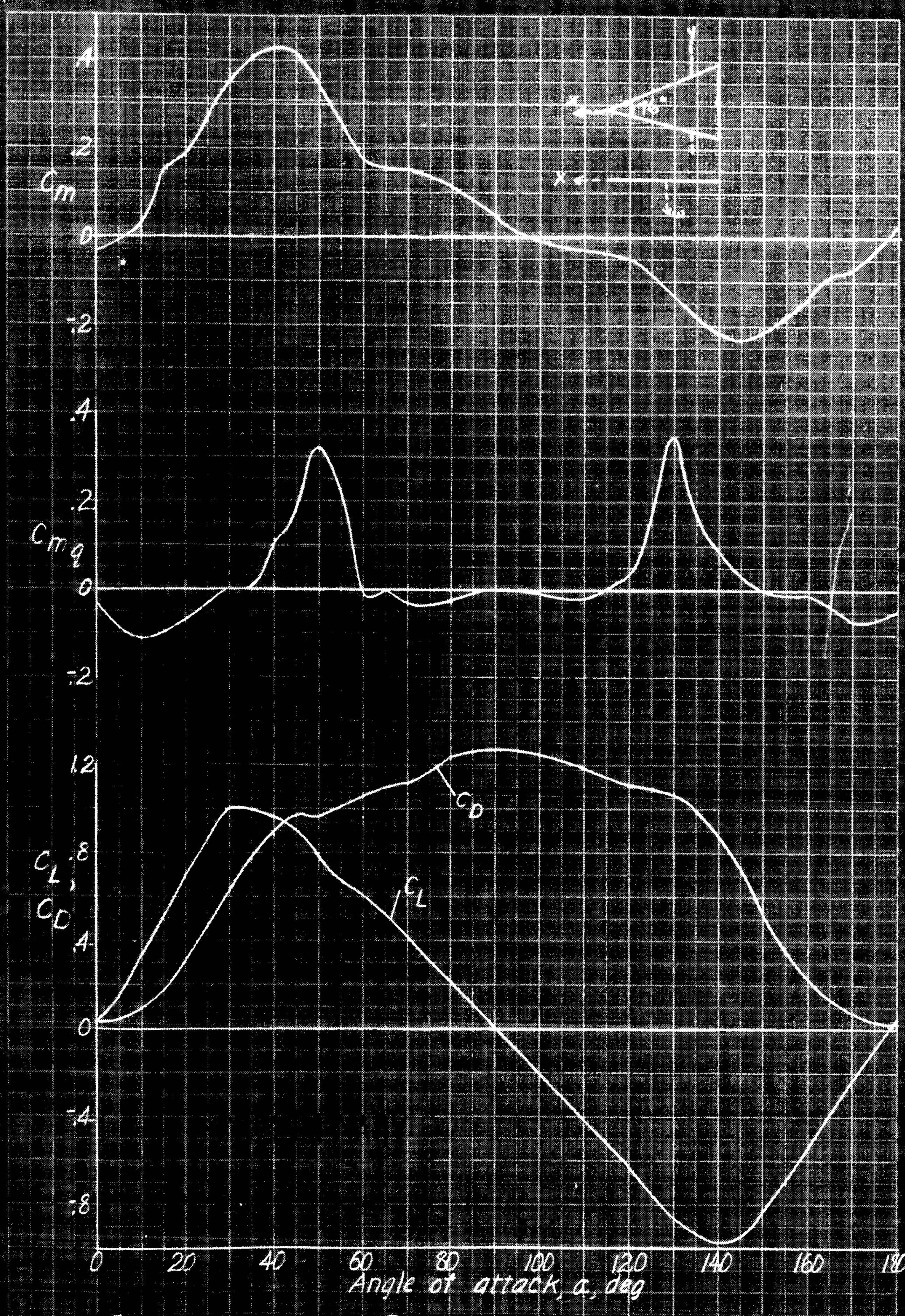

Figure 2—Aerodynamic data for basic 76° delta flat plate

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A number of proposals have been made for vehicles which reenter the earth's atmosphere at very high angles of attack, and then later make a transition maneuver to low angle-of-attack flight. An analytical investigation has been made to determine the requirements in static and damping aerodynamic factors for prevention of end-over-end motions and for limiting oscillations to reasonable amplitudes and frequencies for such a craft when near or at 90° angle of attack. Charts are presented showing the requirements in terms of the longitudinal aerodynamic factors C_{m_α}, C_{L_α}, and C_{m_q}. These requirements may be applied at any Mach number by proper numerical adjustment to the damping derivative. The effects of mass loading variations and of altitude are included. The methods used are applicable for any desired reentry angle of attack and

are presented

Correlations ~~is made~~ with available dynamic model tests. ~~Subsequent work will include~~ a determination of how various longitudinal and lateral aerodynamic design factors would affect the transition maneuver to low-angle-of-attack flight.

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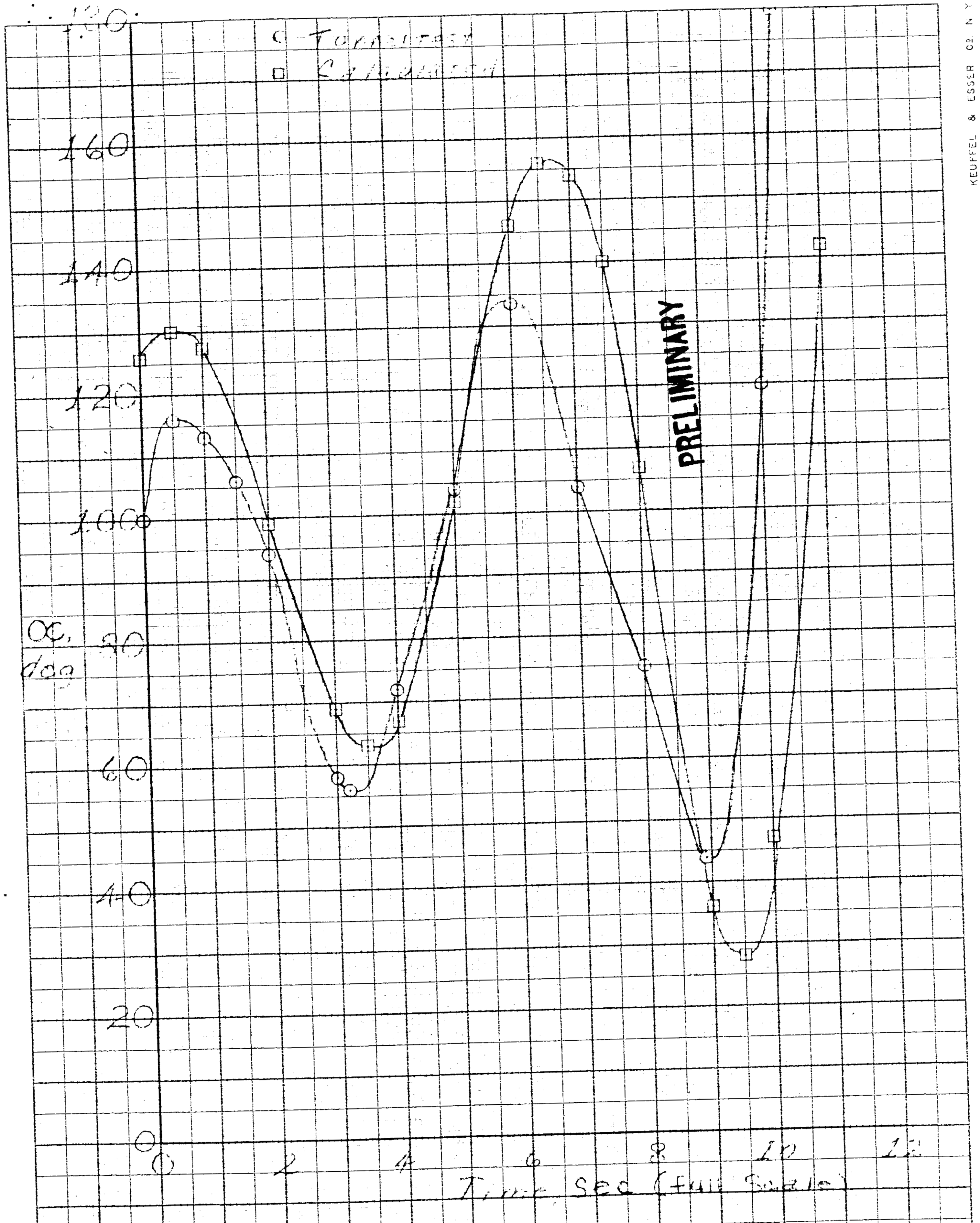


Figure 8 — Comparison of experimental and calculated motion for 7[illegible]

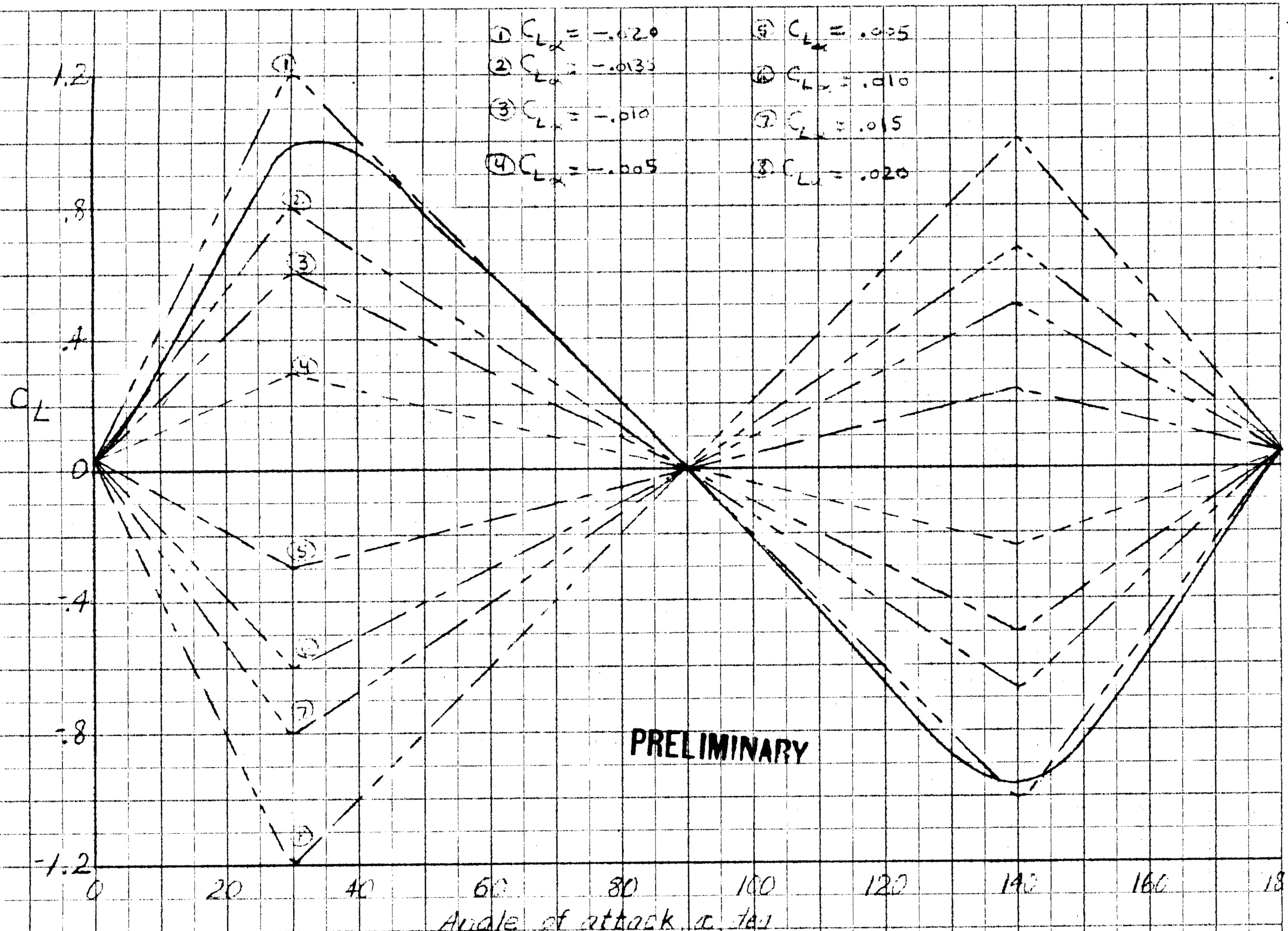


Figure 4 — Variations of C_L with angle of attack

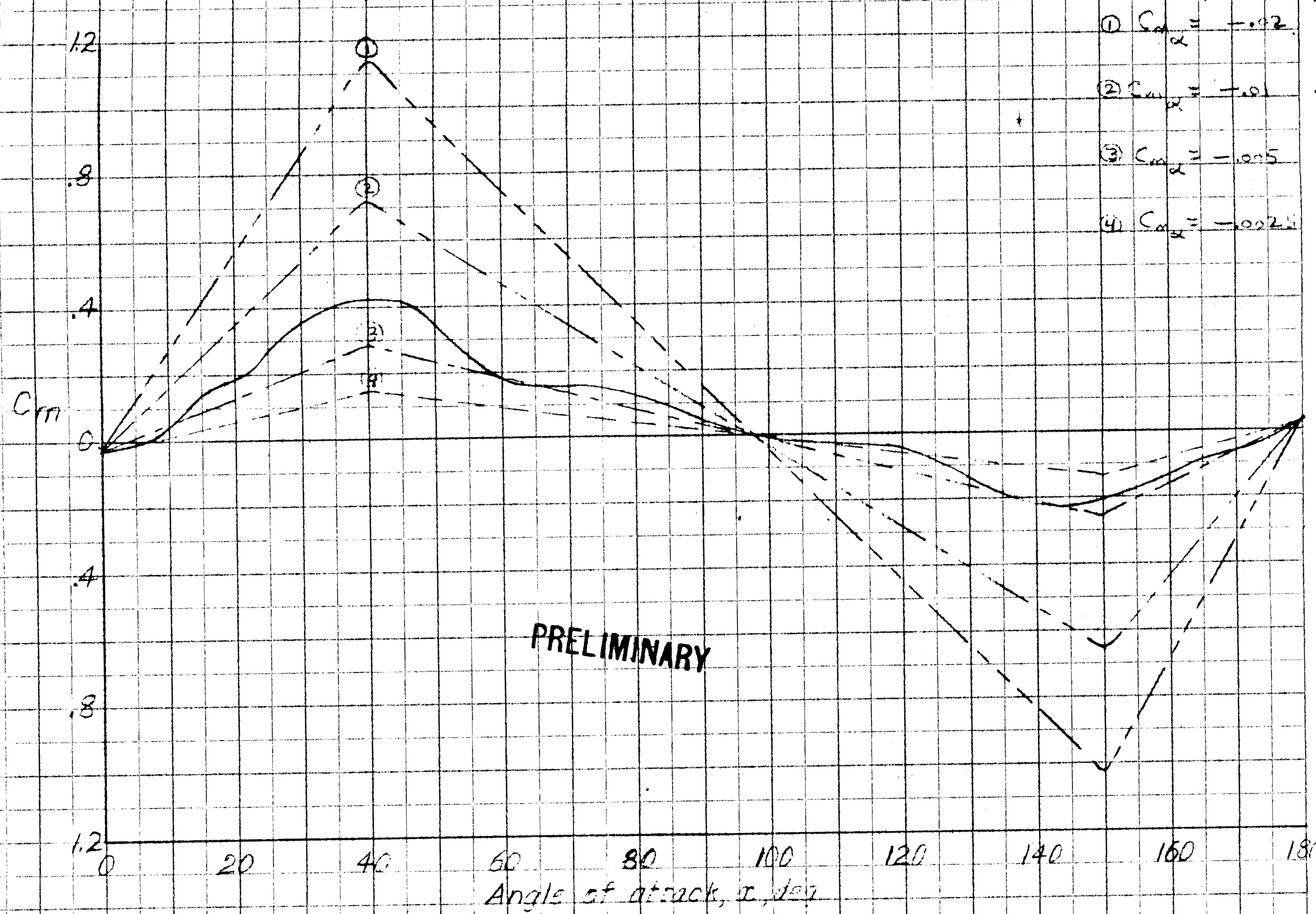


Figure 5 — Variations of C_m with angle of attack

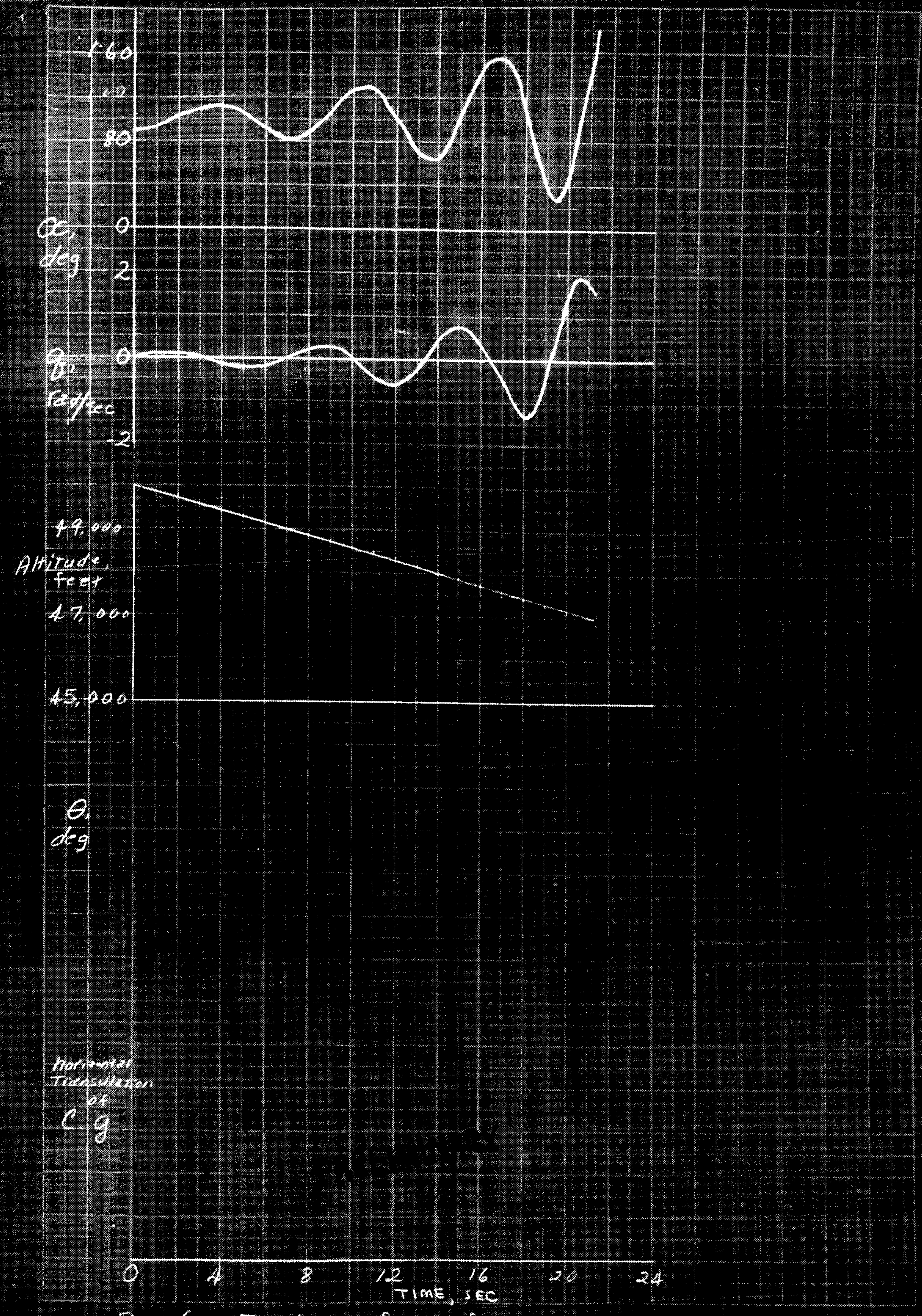
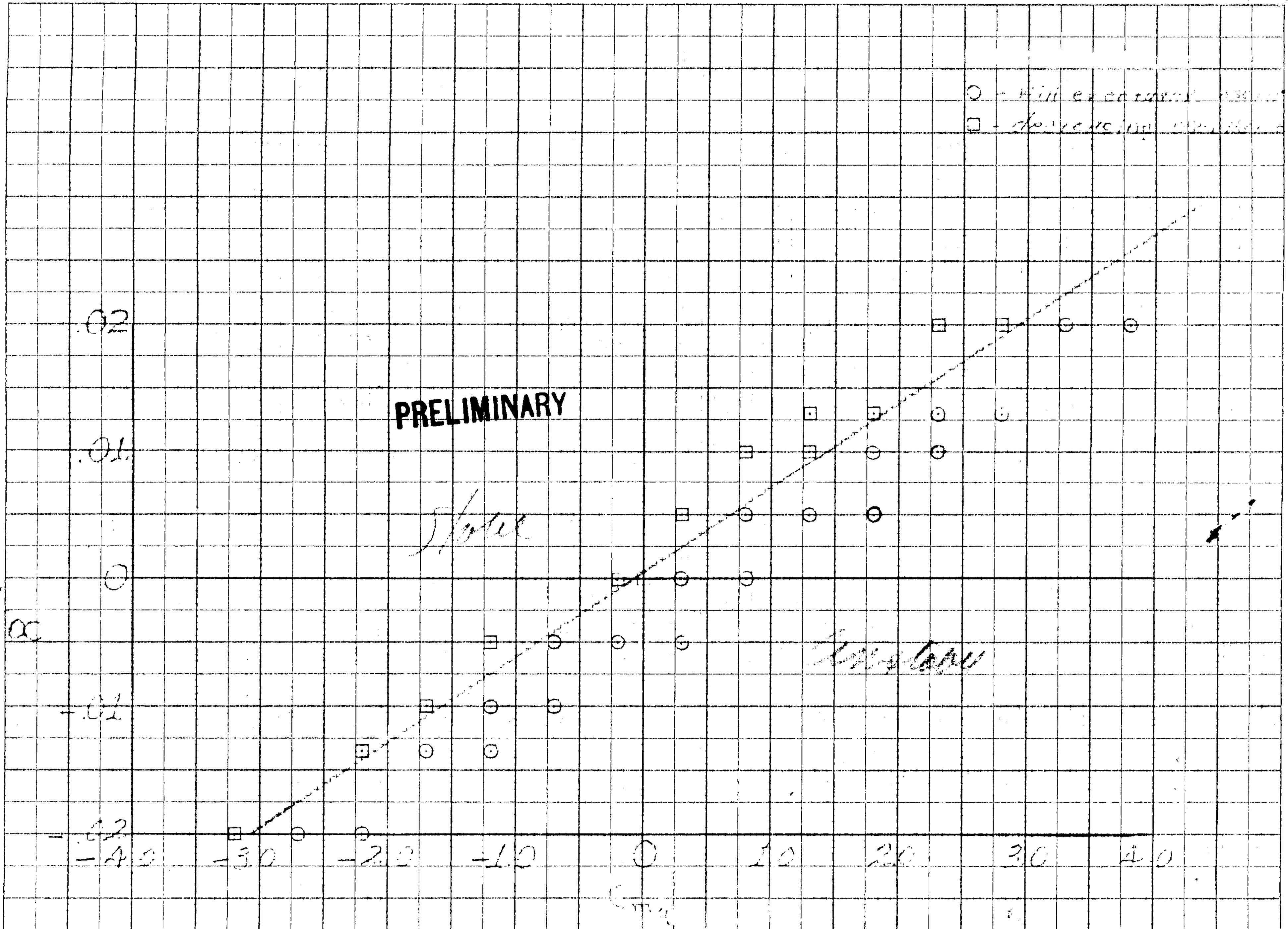
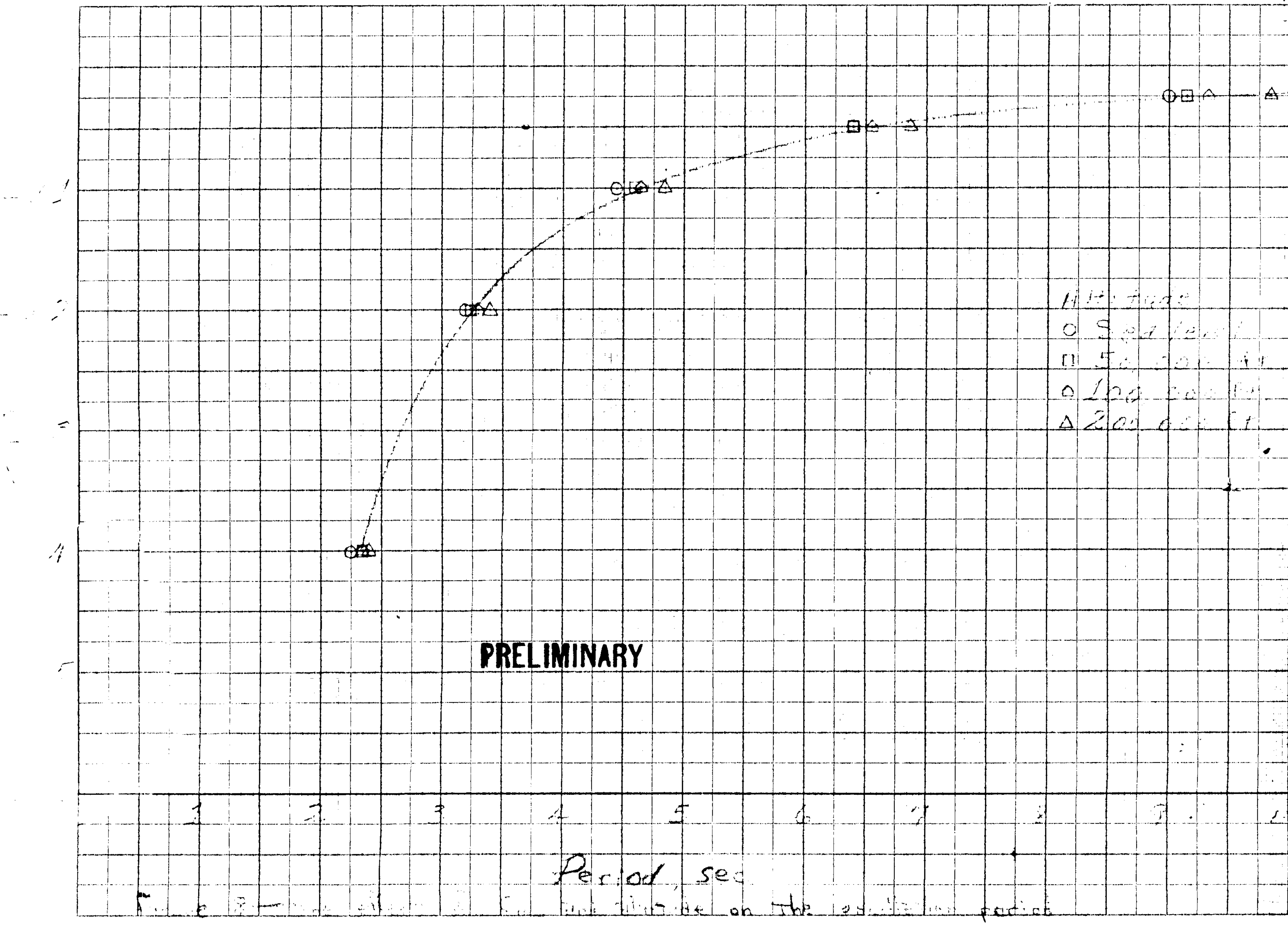


Figure 6 — Time history of angle of attack, pitching moment, altitude, θ_e and horizontal translation of the cg for the 76° delta flat-plate.



F... stability boundary for variations in $C_{m_{\dot{\alpha}}}$ and C_{m_q}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